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DMIC

DEVELOPMENTS

Steels

20, 1967

STEELS FOR HYDROSPACE

In a recent paper, the requirements of steels for hydrospace applications were reviewed, the programs in progress to meet these requirements were described, and the current status of the development of steels for hydrospace was summarized.(1) In order to maintain the dominance of steel in hydrospace application, new steels with significantly increased strength must be developed without sacrificing notch toughness, corrosion resistance, fatigue strength, designability, fabricability, producibility, or economy. The adoption of the leak-before-fracture approach to the fabrication of hydrospace vehicles indicates that the Charpy V-notch energy absorption for 1-inch-thick plates must be increased progressively from 40 to 100 ft-lb as the yield strength increases from 100 to 250 ksi. For 2-inch-thick steel plates, the corresponding energy-absorption range should be about 75 to 200 ft-lb.

Recent steel developments indicate that strength and toughness requirements for 150 ksi yield-strength steel essentially have been met, that the requirements for the 200 ksi yield-strength steel are a near-term probability, and that the requirements for the 250 ksi yield-strength steel are a long-term possibility. The most serious obstacle to meeting the full range of predictions is the attainment of high toughness in plates 6 to 8 inches thick. Thus, special designs, such as those employed in multilayer vessels, may be required for heavy-wall hydrospace vehicles.

The preceding accomplishments and predictions are based on (1) the progress that has been made in the past few years in the melting of steels with greatly reduced levels of impurity elements, (2) the development of entirely new high-strength, high-toughness steel systems, and (3) the discovery of new processing techniques that greatly increase the toughness of steels.

Figure 1 shows the strength-toughness relationships for several ultrahigh-strength steels compared with the optimum materials trend line developed by the Naval Research Laboratory to indicate the current state of development of high-strength, high-toughness steels.

The 10Ni-8Co-2Cr-1Mo-0.1C, dual-strengthened steel recently developed by U. S. Steel exhibits an exceptional combination of yield strength (185 ksi) and toughness (95 ft-lb). Although extensive evaluations will be required before this type of steel will be commercially available, it is the primary basis for projecting the near-term development of a steel with 100 ft-lb energy absorption at 250 ksi yield strength for 1-inch-thick plate and 150 ft-lb at 200 ksi for 2-inch-thick plate.

The development of the rapid heat-treating process, which consists of rapidly austenitizing and quenching a steel as many times as is necessary to refine the austenite grains to an ASTM grain size finer than about No. 13, has resulted in significant improvements in the strength-toughness relationships. The grain refinement results in increased strength with little or no loss in ductility and notch toughness. Also the ductile-brittle transition temperature is lower for rapidly heat-treated steels.

The new steel systems are being developed with appropriate consideration of the requirements for base-metal weldability, compatible weld metals, and improved welding techniques to assure that they will be readily weldable. In addition, coordinated and comprehensive evaluation programs are being conducted to evaluate the suitability of new weldment systems for hydrospace applications.

DEVELOPMENT OF HY-110 WELDMENT

Investigators at United States Steel Corporation's Applied Research Laboratory have continued the work on the development of an HY-110 weldment having a minimum yield strength of 105 ksi after tempering at 1150 F, and a Charpy V-notch impact-energy absorption of 100 ft-lb at -120 F.(2) These steels are nickel-chromium-molybdenum steels with the following composition ranges:

Plate Thickness, inches	Composition Range, weight percent			
	C	Ni	Cr	Mo
Through 2	0.09 to 0.13	2.75 to 3.25	0.80 to 1.20	0.45 to 0.60
Over 2 - through 4	0.08 to 0.12	4.00 to 4.50	1.20 to 1.60	0.60 to 0.75
Over 4 - through 6	0.06 to 0.10	4.50 to 5.00	1.50 to 2.00	0.65 to 0.80

Evaluation of plates obtained from three production heats of light-, intermediate-, and heavy-gage compositions showed that good strength and toughness could be achieved in the nickel-chromium-molybdenum steels of relatively high alloy content. Except for the light-gage plates, the predicted strength and toughness properties generally were not met; however, this was attributed to the high sulfur content of the heats.

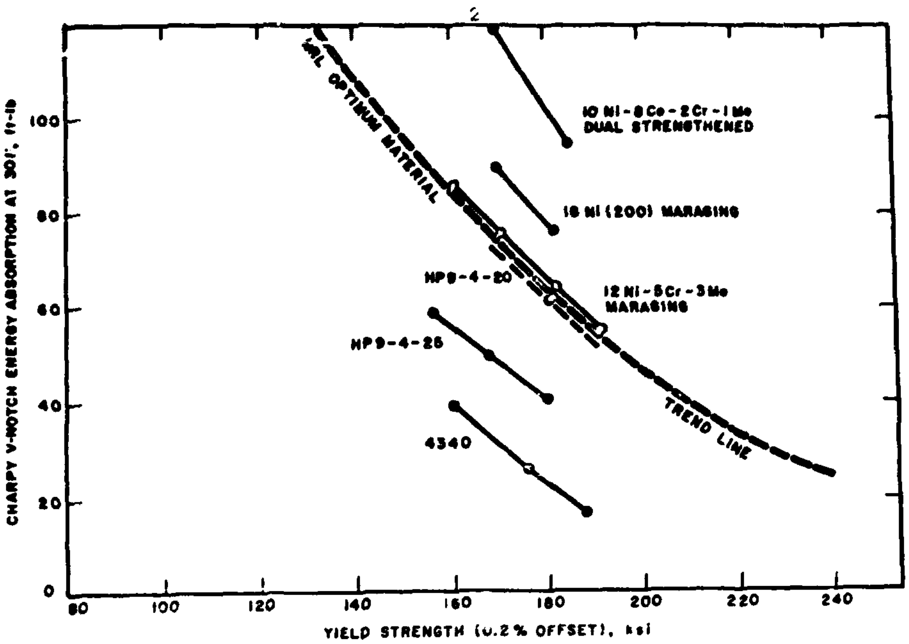


FIGURE 1. STRENGTH-TOUGHNESS RELATION FOR VARIOUS ULTRAHIGH-STRENGTH STEELS COMPARED WITH NRL OPTIMUM MATERIAL TREND LINE(1)

To determine whether less costly HY-110 steels could be developed, a statistically designed laboratory study was undertaken to evaluate vanadium as a replacement for nickel, chromium, and molybdenum. Although this phase of the experimental program is not completed, preliminary results indicate that vanadium additions can be used to develop a more economical HY-110 steel.

AUSFORMABLE, NITRIDABLE STEEL

British researchers have investigated nitridable versions of RARDE* steel, and also the effects of aluminum as an alloying element in steel.(3) Results of these studies led to the concept of combining the advantages of ausforming and nitriding. Two vacuum-melted steels were used in these studies; the chemical compositions of these steels are shown in Table 1. The steels were evaluated in the quenched and tempered condition and in the ausformed (80 percent reduction by rolling) and tempered condition. The mechanical properties of the steels after these treatments are shown in Table 2.

The ausformed A-1857 material showed increases of 22 percent and 9 percent, respectively, for the 0.1 percent offset yield strength and ultimate tensile strength. The corresponding increases for A-1858 were 24 percent and 15.3 percent. The ductility was affected very little by these increases in yield strength, and the Charpy V-notch impact-energy absorption was increased 32 percent for Steel A-1857 and 24 percent for Steel A-1858.

The fatigue endurance limit (Rolls-Royce-type test at 5,000 cpm) of Steel A-1857 was increased from 132 ksi to 143 ksi by ausforming. Nitriding the quenched and tempered steel raised the endurance limit from 132 ksi to 157 ksi; similar treatment of the ausformed steel increased the endurance limit from 143.4 ksi to 174.5 ksi. Thus, the overall increase in fatigue strength of Steel A 1857 by ausforming and nitriding was 32 percent.

Ausforming had little effect on the endurance limit of Steel A-1858, but nitriding the quenched tempered material raised the endurance from 130 ksi to 150 ksi. Similar treatment of the ausformed steel raised the endurance limit from 130 ksi to 156.7 ksi, an increase of 20.5 percent.

The investigators concluded that it is practicable to formulate economical steel compositions that develop good mechanical properties and that can be successfully ausformed and subsequently nitrided.

EFFECT OF EXPOSURE TO ELEVATED TEMPERATURE ON THE MECHANICAL PROPERTIES OF MARAGING STEEL

A recent study at Watervliet Arsenal determined the effect of exposure to elevated temperatures up to 1250 F on the mechanical properties of several heats of 18Ni(250) maraging steel.(4) The work was conducted as one phase of a program to evaluate the suitability of 18Ni(250) maraging steel for mortar tubes.

The specimens used were from five different vacuum-melted heats and were aged at 925 F for 3 hours prior to exposure. The effect of exposure times of 0.5, 1.5, and 8 hours at temperatures in the range of 1000 to 1250 F, and the effect of cyclic 15-minute exposures at 1100 F for 1 to 25 cycles were determined. The results of these experiments are presented in Tables 3 and 4.

These data show that the yield strength of 18Ni(250) maraging steel was significantly reduced

*Royal Armament Research and Development Establishment.

TABLE 1. CHEMICAL COMPOSITION OF THE EXPERIMENTAL STEELS PREPARED BY THE ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT(3)

Steel Identification	Chemical Composition, weight percent								
	C	Si	Mn	S	P	Mo	V	Cu	Al
A-1857	0.37	1.84	2.29	0.004	<0.002	0.78	0.26	1.65	1.14
A-1858	0.35	0.56	2.05	0.009	0.003	0.85	0.26	0.06	1.13

TABLE 2. MECHANICAL PROPERTIES OF THE EXPERIMENTAL RARDE STEELS(3)

Steel Identification	Ultimate Tensile Strength, psi	0.1% Proof Stress, psi	Elongation in 1.4 inches, percent	Reduction in Area, percent	Charpy V-Notch Energy Absorption, ft-lb
		A. Quenched and Tempered at 1110 F			
A-1857	239,000	205,500	12.9	35	8.7
A-1858	215,000	190,000	14.4	50	13.4
		B. Ausrolled and Tempered at 1110 F			
A-1857	260,500	251,000	12.8	36	11.5
A-1858	248,000	237,000	13.8	44	16.6

TABLE 3. MECHANICAL-PROPERTY DATA -- SUSTAINED-ELEVATED TEMPERATURE EXPOSURE OF 18Ni(200) MARAGING STEEL(4)

Exposure Temperature, F	Exposure Time, min	Ambient Temperature Yield Strength, psi	Ambient Temperature Reduction in Area, percent	Elevated Temperature Yield Strength, psi	Elevated Temperature Reduction in Area, percent	Charpy V-Notch at -40 F	Heat
As-aged	--	239.4	20.2	--	--	5.5	1
As-aged	--	240.9	19.1	--	--	6.0	1
As-aged	--	246.9	36.8	--	--	6.5	2
As-aged	--	247.8	39.0	--	--	8.0	2
1000	0.5	232.5	18.2	106.8	56.6	6.0	1
1000	0.5	239.7	29.5	116.7	70.1	8.0	2
1000	1.5	230.7	18.7	85.2	55.9	6.5	1
1000	1.5	239.4	38.0	92.1	78.4	7.0	2
1000	8.0	216.0	18.7	83.4	74.6	5.5	1
1000	8.0	228.6	33.6	94.2	82.3	7.5	2
1100	0.5	177.0	22.7	75.1	97.0	9.5	1
1100	0.5	195.6	35.0	80.7	96.9	11.0	2
1100	1.5	165.0	28.0	44.6	94.3	12.5	1
1100	1.5	184.8	42.1	51.0	99.0	12.5	2
1100	8.0	145.5	28.0	44.7	95.0	12.5	1
1100	8.0	162.0	44.9	52.5	99.0	14.0	2
1150	0.5	136.5	24.6	44.4	97.7	18.5	1
1150	0.5	154.8	48.0	39.3	98.5	20.0	2
1150	1.5	110.7	32.2	30.0	98.0	21.5	1
1150	1.5	123.0	50.4	48.0	99.2	21.0	2
1150	8.0	80.0	32.3	36.5	98.3	19.5	1
1150	8.0	91.8	50.3	37.2	97.9	18.5	2
1200	0.5	114.6	29.5	24.0	98.0	22.5	1
1200	0.5	128.1	50.6	22.6	98.5	23.0	2
1250	0.5	83.4	34.0	18.0	99.0	16.0	1
1250	0.5	80.4	51.7	17.3	98.9	23.0	2

TABLE 4. MECHANICAL-PROPERTY DATA -- CYCLIC ELEVATED-TEMPERATURE EXPOSURE[a] OF 18Ni(200) MARAGING STEEL[4]

		Ambient Temperature		Elevated Temperature			
Exposure Temperature, F	Exposure Cycles	Yield Strength, psi	Reduction in Area, percent	Yield Strength, psi	Reduction in Area, percent	Charpy V-Notch at -40 F	Heat
As-aged	--	233.6	36.7	--	--	8.0	3
As-aged	--	235.5	36.3	--	--	6.5	3
As-aged	--	233.4	19.1	--	--	12.0	4
As-aged	--	234.2	20.8	--	--	--	4
As-aged	--	234.0	37.0	--	--	9.0	5
As-aged	--	234.9	39.2	--	--	--	5
1100	1	200.7	35.8	60.6	96.0	6.5	3
1100	1	207.9	38.5	61.4	90.3	10.5	3
1100	1	203.7	39.8	66.1	81.4	8.5	4
1100	1	--	--	62.4	79.7	--	4
1100	1	207.6	39.8	54.5	94.6	10.0	5
1100	1	--	--	54.4	96.6	--	5
1100	5	181.6	38.4	58.6	94.8	9.0	3
1100	5	177.8	38.9	56.5	91.6	11.0	3
1100	5	169.8	23.2	57.4	86.5	13.0	4
1100	5	180.9	34.3	57.2	96.4	13.0	5
1100	10	170.7	40.1	66.2	93.1	11.0	3
1100	10	173.0	40.4	67.6	90.0	12.0	3
1100	10	169.6	17.8	56.2	96.1	13.5	4
1100	10	--	--	62.4	84.5	--	4
1100	10	172.1	42.6	51.9	98.0	17.0	5
1100	10	174.2	42.1	--	--	19.0	5
1100	25	165.0	39.4	58.8	96.6	12.0	3
1100	25	166.9	44.7	59.6	94.7	16.5	3
1100	25	160.0	18.8	56.1	83.1	14.5	4
1100	25	155.7	23.2	--	--	12.0	4
1100	25	166.6	40.4	48.6	96.1	16.0	5
1100	25	--	--	54.4	93.3	--	5

(a) 15 mintues per cycle.

by exposure to temperatures in excess of 1000 F, and that the reduction was most significant in the initial half hour of exposure. With increased exposure, the ductility at elevated temperatures, as measured by reduction in area, approached 100 percent and thus reduced the probability of catastrophic failure at elevated temperatures. The data developed for cyclic exposures show that the effect of time at temperature was cumulative; for example, four 15-minute cycles were equivalent to one 60-minute exposure. The investigators concluded that if a yield strength of 70 ksi at temperature is required, the maraging steel tubes should not be exposed to temperatures in excess of 1050 F for times longer than 0.5 hour. Any application of these steels in mortar tubes will require appropriate consideration of their temperature limitations, particularly in respect to rate of fire, which determines the heat input.

STRESS-CORROSION CRACKING IN 9Ni-4Co STEELS

McDonnell-Douglas conducted an extensive program to determine the susceptibility of HP 9Ni-4Co steels to stress-corrosion cracking.[5] Particular emphasis was on the effect of processing variables that are encountered during fabrication of the material into a serviceable part. The materials used in this evaluation were HP 9-4-30 (plate) heat treated to the 220/240 ksi ultimate-tensile-strength range with tempered-martensite microstructure, and HP 9-4-45 (billet) heat treated to the 260/280 ksi ultimate-tensile-strength range with both bainite and tempered-martensite microstructures. Stress-corrosion testing was conducted by alternate immersion in synthetic seawater for 1000 hours under sustained loads of 80 percent of the yield strength for HP 9-4-45 and 85 percent of the yield strength for HP 9-4-30. In addition, a limited number of tests were conducted using a cycle of 22 hours alternate immersion and 2 hours at 400 F in air for a total of 1000 hours to simulate advanced aircraft service.

The results of this study are summarized in Figures 2, 3, and 4. The HP 9-4-30 steel (Figure 2) was susceptible to stress-corrosion cracking after severe dry-grinding and through-hole-drilling operations after heat treatment. The processes produced surface discoloration and an underlying layer of untempered martensite. A 950 F stress relief after dry grinding re-established immunity to stress-corrosion cracking. Fusion-welding (TIG) of this material drastically lowered stress-corrosion resistance (HAZ failures). A 950 to 1050 F stress relief produced some improvement, but a subsequent shot-peen operation was necessary to restore immunity. Untempered martensite in this

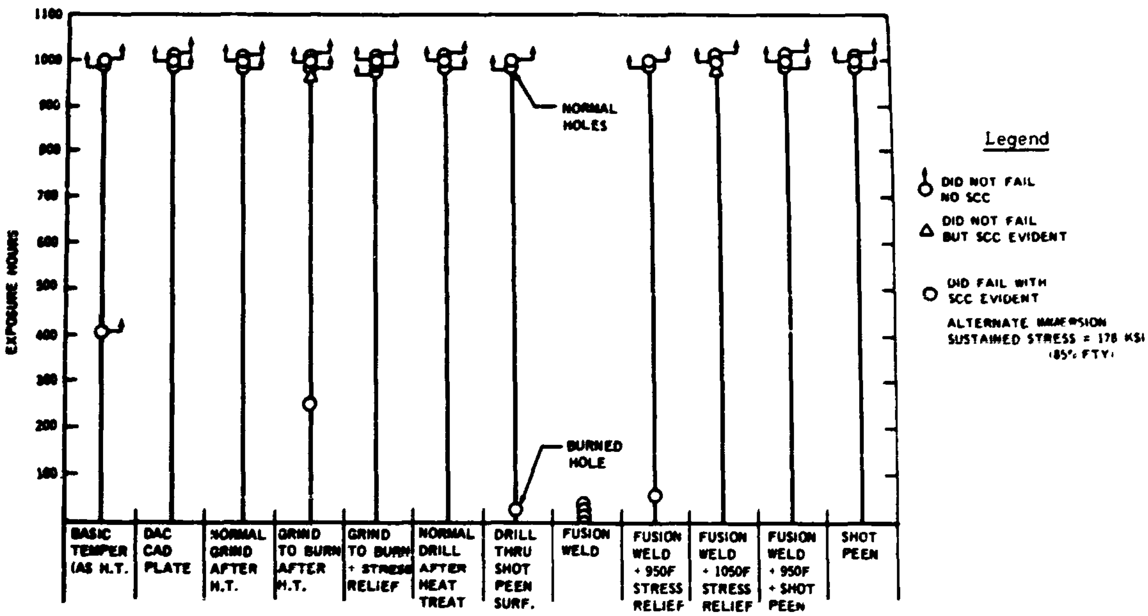


FIGURE 2. EFFECT OF PROCESSING VARIABLES ON STRESS-CORROSION CRACKING (SCC) OF HP 9-4-30 MARTENSITE, 220/240 KSI ULTIMATE STRENGTH(5)

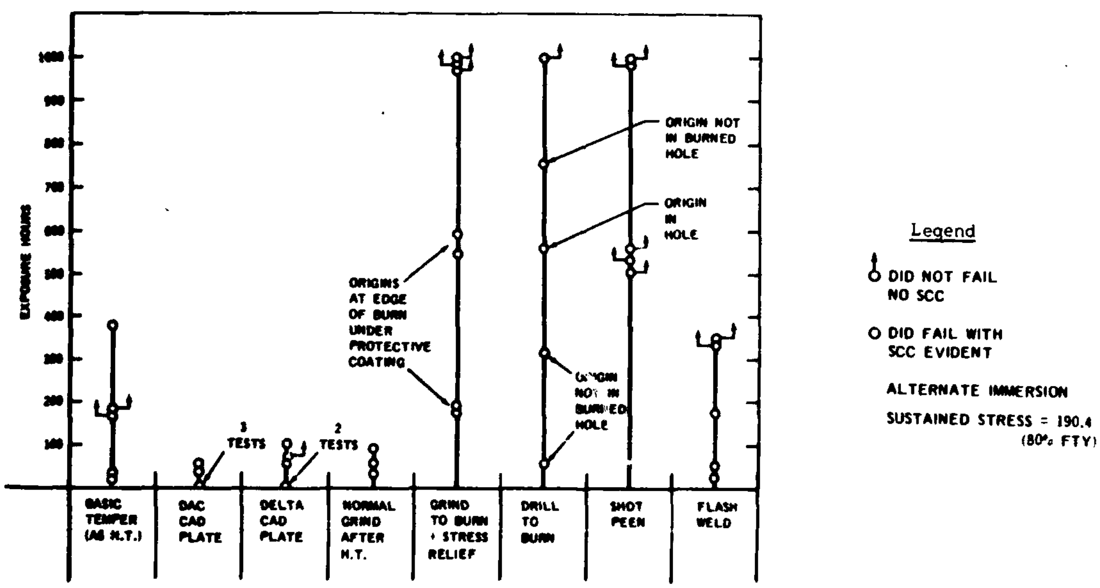
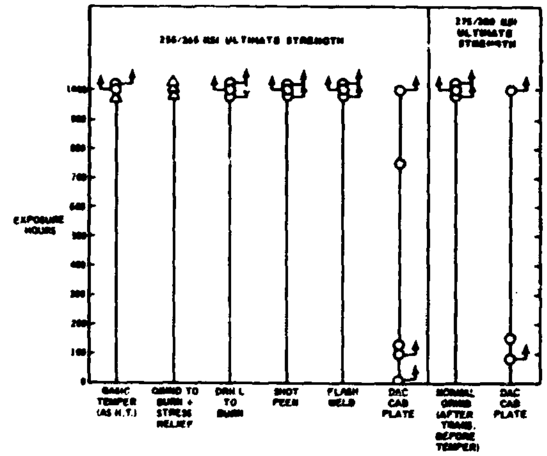


FIGURE 3. EFFECTS OF PROCESSING VARIABLES ON STRESS-CORROSION CRACKING (SCC) OF HP 9-4-45 MARTENSITE, 260/280 KSI ULTIMATE STRENGTH(5)



Legend

DID NOT FAIL, NO SCC

DID NOT FAIL, BUT PIT OR SCC EVIDENT

DID FAIL WITH SCC EVIDENT

ALTERNATE IMMERSION

SUSTAINED STRESS = 175.6 KSI

FIGURE 4. EFFECTS OF PROCESSING VARIABLES ON STRESS-CORROSION CRACKING (SCC) OF HP 9-4-45 BAINITE, 255/265 KSI AND 275/280 KSI ULTIMATE STRENGTH RANGES(5)

alloy was susceptible to stress-corrosion cracking, but to cause cracking in tempered martensite, a critical, but shallow, mechanical crack or stress-corrosion crack from untempered into tempered martensite was necessary. The stress-corrosion cracking threshold stress (applied plus residual) for tempered martensite was determined to be above 205 ksi and for untempered martensite between 90 and 120 ksi.

The HP 9-4-45 martensite (Figure 3) was very susceptible to stress-corrosion cracking for all variables tested except shot peening. The cadmium-plated steel was the most susceptible. The net stress-corrosion cracking stress for tempered martensite was between 89 and 127 ksi.

The HP 9-4-45 untempered bainite (Figure 4) at 255/265 ksi ultimate tensile strength was immune to stress-corrosion cracking in the as-heat-treated, heat-treated and shot-peened, and flash-welded and heat-treated conditions. HP 9-4-25 bainite transformed at lower temperature followed by tempering (275/280 ksi ultimate tensile strength) appeared to be as resistant to stress-corrosion cracking as the lower strength bainite. Cadmium plating lowered the stress-corrosion resistance of the HP 9-4-45 bainite, as it did with the HP 9-4-45 martensite. Severe grinding and severe drilling conditions resulted in stress-corrosion cracks only in the martensite surface layer; these cracks did not propagate into the bainite. Precracked samples of the HP 9-4-45 bainite were also susceptible to stress-corrosion cracking.

The advanced aircraft thermal cycle (2 hours in air at 400 F, 22 hours in alternate immersion) increased the stress-corrosion cracking resistance of all alloys under the conditions tested. This behavior was attributed to the development, during the 400 F cycle, of a continuous, nonporous oxide surface film that was impervious to the corrosive environment.

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